Single resonance monolithic Fabry-Perot filters formed by volume Bragg gratings and multilayer dielectric mirrors

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ABSTRACT

High efficiency reflecting volume Bragg gratings (VBGs) recorded in PTR glass plates have shown un-preceded performances that make them very good candidates for narrowband spectral filtering with sub-nanometer spectral widths. However, decreasing the bandwidth to value below 30-50 pm is very challenging as it requires increasing the thickness of the RBG to more than 15-20 mm. To overcome this limitation, we propose a new approach which is a monolithic Fabry-Perot cavity which consists from a reflecting VBG with a multilayer dielectric mirror (MDM) deposited on its surface. A VBG with a grating vector perpendicular to its surface and a MDM produce a Fabry-Perot resonator with a single transmission band inside of the reflection spectrum of the VBG. We present a theoretical description of this new class of filters that allow achieving a single ultra-narrowband resonance associated with several hundred nanometers rejection band. Then we show the methods for designing and fabricating such filter. Finally, we present the steps that we followed in order to fabricate a first prototype for 852 nm and 1062 nm region that demonstrates a 30 pm bandwidth, 90+% transmission at resonance and a good agreement with theoretical simulation.

Keywords: Volume Bragg gratings, Fabry-Perot, Ultra-narrowband filters

1. INTRODUCTION

Since the invention of laser holography, scientists have been looking for the ideal medium for hologram recording [1]. Much research has been directed towards holographic data storage in photorefractive crystals and photopolymers. But these materials are unsuitable for high power laser applications due to their low laser damage threshold. Recently a new photosensitive material named photo-thermo-refractive (PTR) glass was developed and high-efficiency volume holographic optical elements were demonstrated [2,3]. PTR diffractive optical elements have shown high robustness under harsh conditions of utilization at elevated temperatures and under high power laser irradiation. These elements have been successfully used for spectral beam combining, selection of transverse and longitudinal modes in different laser resonators, beam deflectors, splitters, attenuators, etc.

2. THEORY

High efficiency reflecting Bragg gratings (RBGs) can be recorded in PTR glass plates with thicknesses of a few millimeters. These elements are narrowband spectral filters with sub-nanometer spectral widths. However, decreasing the bandwidth to value below 30-50 pm is very challenging as it requires increasing the thickness of the RBG to more than 15-20 mm. To overcome this limitation, several alternative solutions were previously proposed: the incoherent combination of a Fabry-Perot etalon and a RBG [4], pi-shifted volume Bragg gratings [5], the multiplexing of two RBG within one PTR glass for the fabrication of moiré Bragg gratings [6]… In this paper we propose a new approach which is a monolithic Fabry-Perot cavity produced by two mirrors which are a RBG with a multilayer dielectric mirror (MDM) deposited on its surface (RBG/MDM filter), Fig. 1.

Optical Components and Materials IX, edited by Shibin Jiang, Michel J. F. Digonnet, J. Christopher Dries,
Proc. of SPIE Vol. 8257, 82570I · © 2012 SPIE · CCC code: 0277-786X/12/$18 · doi: 10.1117/12.908199

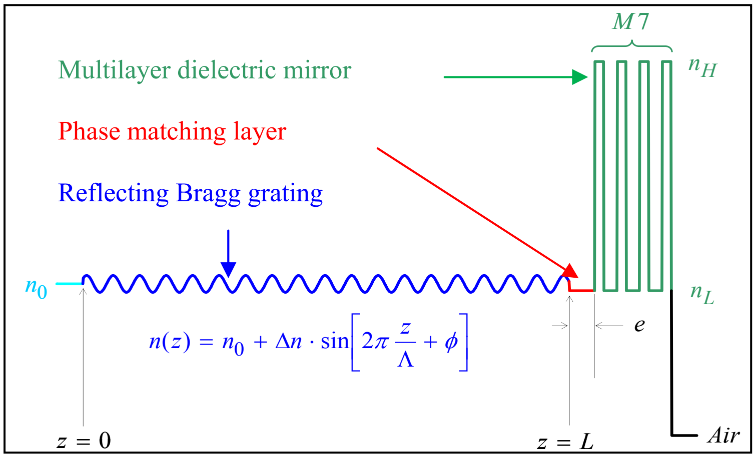

Fig. 1. Spatial profile of refractive index in a RBG/MDM filter formed a reflecting Bragg grating and multilayer dielectric mirror with a phase matching layer

Such a filter was demonstrated in guided configuration using fiber Bragg gratings [7] but no experimental demonstration in free space could be done with the unavailability of materials for recording high quality volume Bragg gratings. Spectral response of the Bragg-dielectric filter resulting from the coherent combination of a RBG (Bragg wavelength: 852 nm, thickness: 2.84 mm, refractive index modulation: 170 ppm and a MDM (with 9 quarter-wave alternated layers) was modeled by decomposing the RBG into elementary homogeneous thin layers and applying the admittance theory for thin films on the whole RBG/MDM assembly [8]. A typical spectral shape for RBG/MDM filter calculated with the mentioned model is shown in Fig. 2. This filter is a Fabry-Perot resonator formed by two mirrors. This filter reflects a broadband corresponding to the reflection band of the MDM. But the main feature of this filter is that an ultra-narrow band resonance appears at the Bragg wavelength of RBG. This resonance corresponds to a high transmission line of the filter. It is important that the resonance can be observed, even if the gap between the RBG and the MDM is equal to zero. This is due to the fact that the RBG is a resonant cavity itself [5] as it acts as a virtual plane mirror situated at a certain distance from its front surface. This distance depends on the thickness and diffraction efficiency of the RBG [8]. Theoretically this transmission at resonance is equal to 100% if the RBG and the MDM have identical reflection coefficients at the Bragg wavelength. One can see that very close to the resonance (in the range where diffraction efficiency of the RBG is not zero) rejection will be high (generally much better than 15/20 dB) due to the coherent nature of the combination between both types of mirrors. Then, in a broader range, rejection is given by the reflection coefficient of the DM and therefore is limited to 10 dB for 90% reflection MDM but can be increased by increasing the MDM's reflection coefficient.

The main challenges in fabricating this class of filters consist in having a resonance condition between the Bragg mirror and the dielectric mirror. We therefore analyzed the methods to satisfy this condition. Let us consider the filter's structure shown in Fig. 1. Coherence conditions can be met by controlling the distance between the RBG and the MDM [7]. Let us first suppose the RBG has a thickness L and the following spatial refractive index modulation:

$$n(z) = n_0 + \Delta n \cdot \sin\left[2\pi \frac{z}{\Lambda} + \phi_i\right] \qquad (1)$$

where n_0 is the PTR glass mean refractive index, Δn the modulation amplitude, ϕ_i the start phase (phase of the modulation at z = 0) and Λ the period of the sine modulation. Let us also suppose that the RBG and the MDM are separated by a matching layer having refractive index n_L and a thickness t. In this case, it is possible to show [7] that the resonance condition can be written as:

$$\Phi = \left[\phi_i + 2\pi \frac{L}{\Lambda}\right] + 2\pi \frac{2 n_L t}{\lambda_0} + \phi_{DM}(\lambda_0) = 0 \quad [2\pi] \qquad (2)$$

where ϕ_{DM} is the phase at reflection of the MDM and λ_0 is the central wavelength of the filter The term into brackets therefore represents the final phase (ϕ_f) of the refractive index modulation of the RBG where contact with the matching layer occurs and the term after represents the phase shift that occurs during the propagation through the matching layer. After recording of the RBG, the values of ϕ_i and therefore ϕ_f are fixed. Hence to fulfill the resonance condition, the value of the overall phase term Φ can be adjusted by simply controlling the physical thickness t of the matching layer. Analysis of Eq. (2) shows that, in order to obtain phase matching between the two structures, the optical thickness of a matching layer must be controlled with a precision better than λ/10. In other words, a precision on the mechanical thickness of ~50 nm is required.

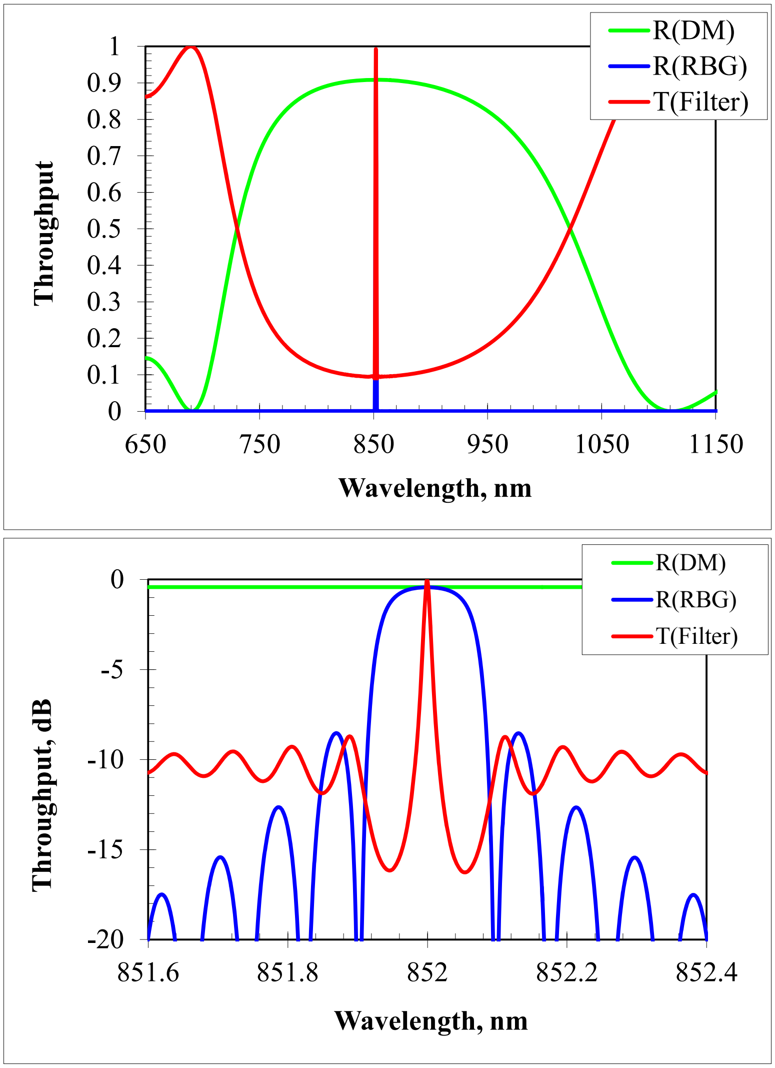

Fig. 2. Transmission spectrum of a RBG/MDM filter (red), and reflection spectra of a MDM (green) and a RBG (blue). Top – linear scale, bottom – logarithmic scale.

At this point, it must be noted that the Fabry-Perot cavity in the proposed device is not formed by two reflecting surfaces, but it is produced by an effective reflecting surface of a MDM and an effective reflecting surface of a volume RBG. These effective reflecting surfaces in both structures are composed with the sums of reflecting planes (planes of iso-refractive index changes) with a total number of several planes for a MDM and but several thousand for a RBG. In order to obtain a high throughput, these planes must be perfectly parallel to each other and very flat. In a classical Fabry-Perot etalon composed with regular plane mirrors, flatness of each mirror must be better than λ/10 and the wedge between the two mirrors must be lower than a few arcseconds in order to have appearance of a very narrow band filter with high throughput [10]. By analogy, both MDM and RBG must have plane of iso-refractive index with high flatness. This condition is easily achieved with a current technology of MDMs and such conditions are met in high efficiency volume diffractive elements in photo-thermo-refractive glass at OptiGrate Corp. In addition, a wedge between the RBG and the MDM must also be very small and comparable to the one which is required between the mirrors of a regular Fabry-Perot etalon. The technology developed at OptiGrate Corp. also allows fabricating reflecting Bragg mirrors with grating vector tilt in regards to one of the glass surface well below 1 mrad. Therefore, it is possible to directly deposit a matching layer (the layer that provides phase matching between RBG and MDM) and a dielectric mirror on one of the facets of a RBG. The fabricated filter will have an ultra-narrow bandwidth and minimum losses resulted from misalignment between mirrors.

3. EXPERIMENTS

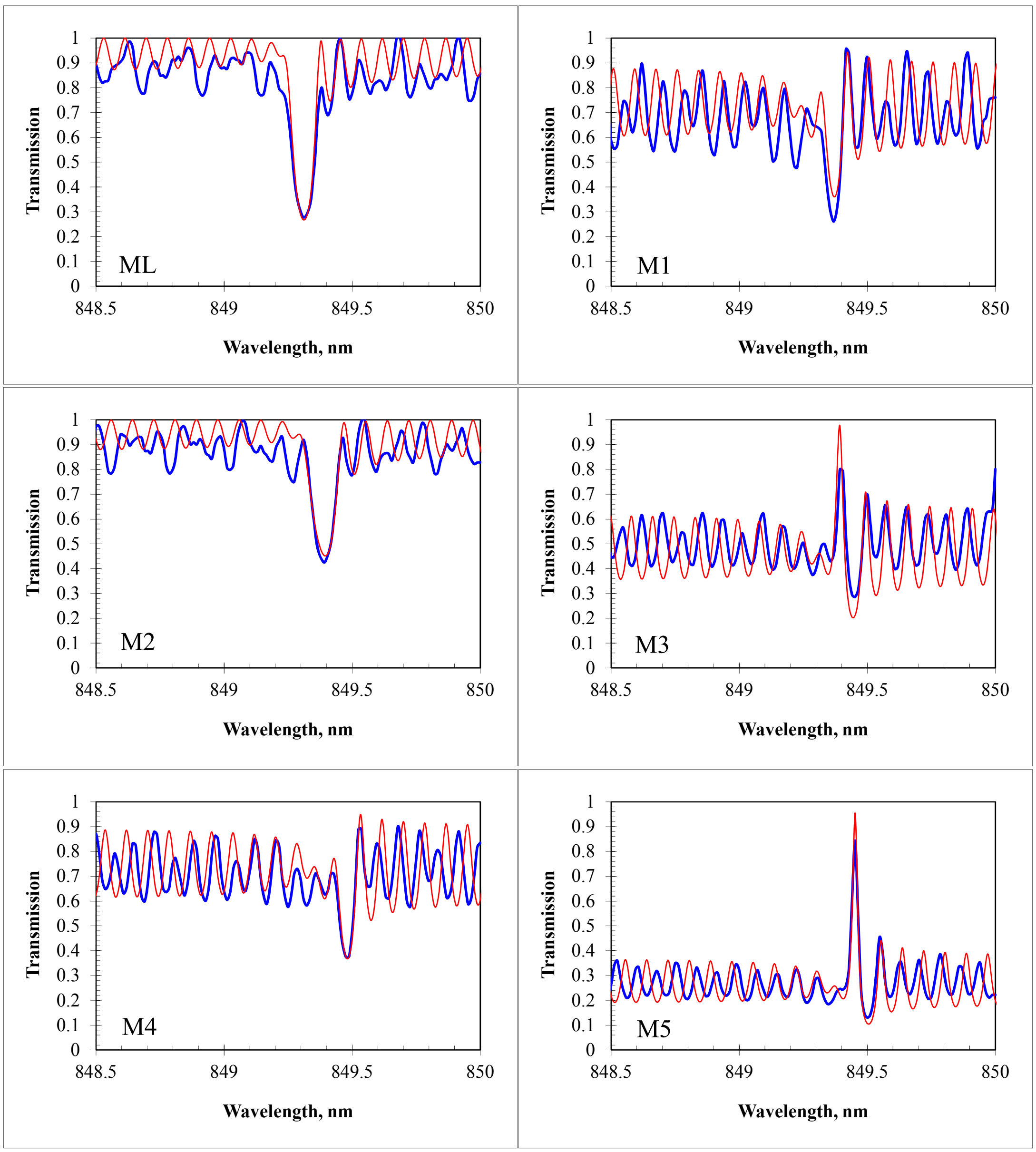

Fig. 3. Evolution of the transmission spectra of the filter during the process of fabrication, i.e. after deposition of the matching layer (ML) and each of the layers of the dielectric mirror (MX). Blue curve is the measurement and red one is the modeling.

To fabricate such a filter at 852 nm, a RBG in PTR glass with thickness of 2.89 mm and diffraction efficiency of ~65% was fabricated. Then a matching layer and a quarter-wave alternated dielectric mirror were deposited on a facet of the RBG by electron beam deposition with ion assistance. The high refractive index layers of an MDM were obtained by depositing tantalum pentoxyde layers (Ta_2O_5) while low refractive index layers were obtained by deposition of silica layers (SiO_2). The matching layer was obtained by depositing a silica layer. Thickness monitoring of each layer was realized by acoustic wave measurement of its weight using a quartz microbalance associated with an in-situ measurement of the transmittance of the assembly with the help of the tunable laser source for 850 nm region and 1 pm spectral resolution, connected to a collimator, and a photodiode associated with a data acquisition card. The control was realized after each layer by scanning the wavelength and measuring the transmitted power. The deposition sequence was the started by depositing a SiO_2 matching layer to correct the end phase of the RBG. Then a 5-layer mirror (Ta_2O_5/SiO_2) was deposited to match as close as possible the reflection coefficient of the RBG. The final reflection coefficient of the dielectric mirror (75%) was however higher than the Bragg mirror (65%). The modeling shows that for such a combination the maximum transmission at resonance is limited to about 90%. The transmission spectra after the each stage of filter fabrication are shown in Fig. 3. One can see how the filter is forming and how the resonance is appearing while the reflection coefficient of the dielectric mirror is changing. It should be noted that the reflection coefficient of a dielectric mirror increased after deposition of a quarter-wave layer of the high refractive index while it is decreasing after deposition of a quarter-wave layer of the low refractive index. Therefore, a resonance can only be seen after deposition of the third and fifth layers of the mirror. Also, it can be seen that the measured transmission spectrum and the theoretical one match quite well.

Finally, after opening the deposition chamber, we measured the transmittance of this RBG/MDM filter around the resonance wavelength (848.5 nm – 850 nm). The comparison of these experimental results with the theoretical predictions is presented in Fig. 4. One can see that the filter transmits more than 80% with a full width at half maximum of ~30 pm. There are some oscillations outside of the main resonance that can be associated with an additional Fabry-Perot cavity produced by Fresnel reflection on the uncoated facet of the PTR glass plate. Some dissymmetry of the transmission spectrum of the filter can be explained by a ~20% error in the thickness of the matching layer.

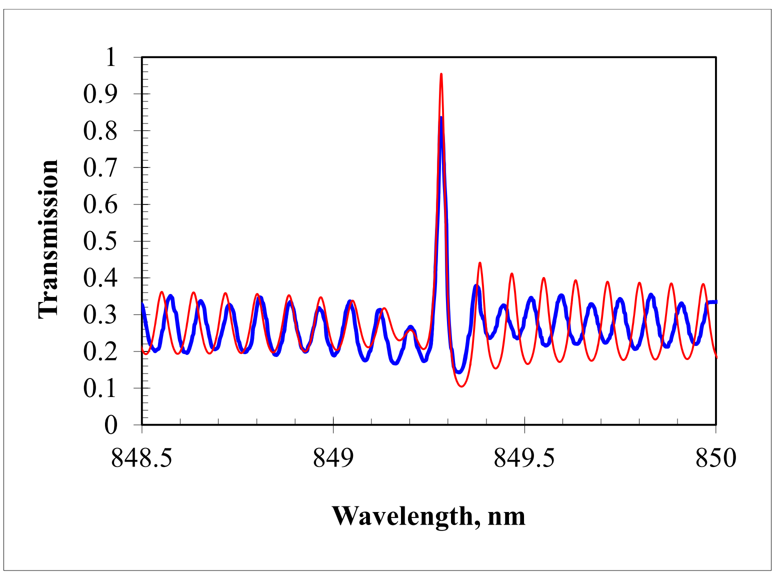

Fig. 4 Transmission spectrum of the RBG/MDM filter in air. Blue – measurement, red - theory.

In order to remove the oscillations in the transmission spectrum outside of the resonance, we then deposited an AR-coating on the rear facet of the RBG. We used a 2 layer AR-coating with classical formula 0.3H/1.3L centered at 850 nm, with theoretical reflection below 0.1%. Then we re-measured the spectral transmission (Fig. 5). One can see that the filter has now very small oscillations outside the resonance. Moreover it transmits 85% and the bandwidth is below 30 pm in 850 nm region. When comparing with theory, one can see that maximum transmission at the resonance is very similar. This limited transmission is due to a mismatch between the reflection coefficients of the Bragg grating (65%) and the dielectric mirror (75%).

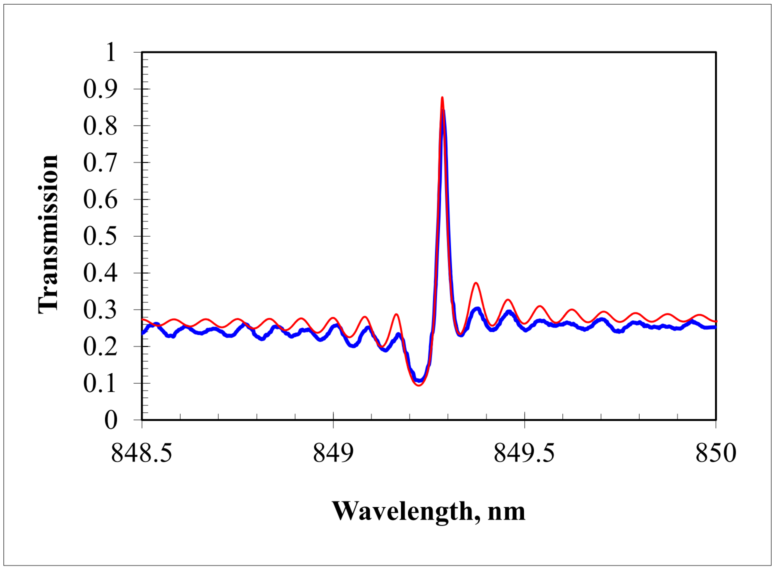

Fig. 5 Transmission spectrum of the filter in air after AR-coating. Blue – measurement, red - theory.

Finally, to demonstrate that this approach can be extended to any wavelength within the transparence rage of PTR glasses (i.e. 350 to 2700 nm) we fabricated a filter for 1064 nm region. A RBG in PTR glass with thickness of 2.6 mm, central wavelength 1061 nm and diffraction efficiency of ~75% was fabricated. Then the back face was AR-coated. To pre-determine the thickness of the matching layer required to obtain a resonance condition, the spectral transmission of the RBG after deposition of the AR-coating was characterized (Fig. 6).

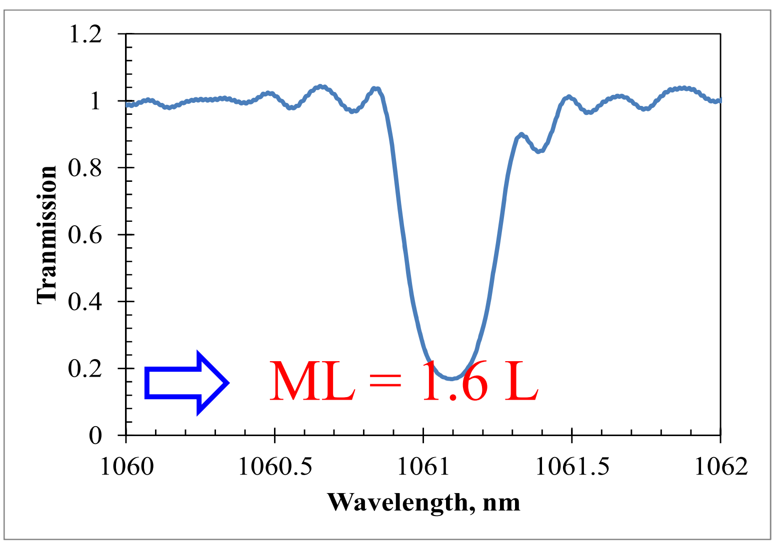

Fig. 6 Transmission spectrum of the RBG at 1061 nm after AR-coating deposition and before deposition of the matching layer and the mirror.

It is seen that the spectrum is asymmetrical. However, it was shown in Ref. [7] that the asymmetry can be predicted and is associated with the presence of a Fabry-Perot cavity formed between the reflecting Bragg grating and the Fresnel reflection on the uncoated face. By modeling it was possible to predetermine the thickness of the required matching layer that was equal to 1.6 × a quarter-wave layer with low refractive index (obtained by depositing a silica layer). Then, to match the reflection coefficient of the two mirrors, a quarter-wave alternated dielectric mirror was deposited on the uncoated facet of the RBG by electron beam deposition with ion assistance. The high refractive index layers of an MDM were obtained by depositing tantalum pentoxyde layers (Ta_2O_5) while low refractive index layers were obtained by deposition of silica layers (SiO_2). Fig. 7 shows the spectral transmission of the filter measured after final fabrication of the filter. This filter presents a single resonance centered at 1061 nm with transmission 90+% and 50 nm FWHM. Rejection is poor due to the low reflection coefficient of the dielectric mirror and filter is not perfectly symmetrical due to non-perfect phase matching. However, this experimental demonstration shows that this approach of Bragg-Dielectric filter can be easily extended to any spectral region.

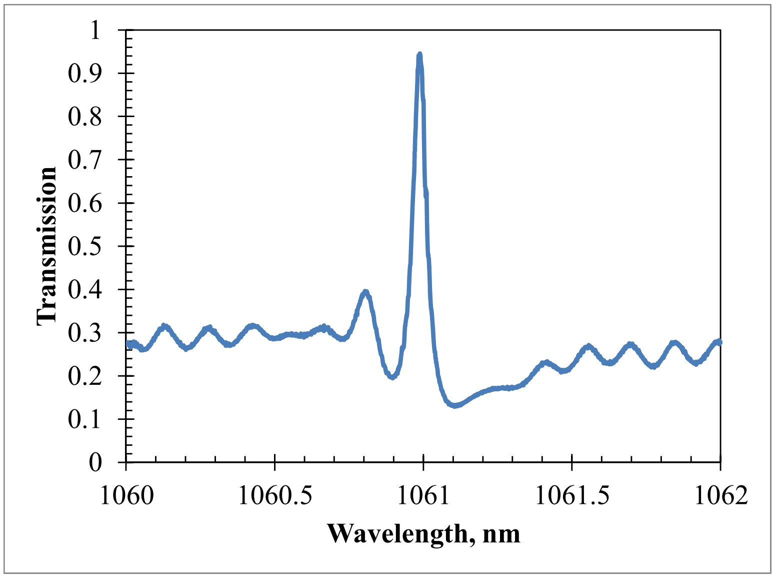

Fig. 7 Transmission spectrum of the filter in air after AR-coating and deposition of the matching layer and dielectric mirror.

4. CONCLUSIONS

We have demonstrated a new class of spectral filters combining a reflecting Bragg grating recorded in PTR glass with a matched multilayer dielectric mirror. The fabricated filters have a bandwidth of 30 and 50 pm respectively at 852 and 1061 nm and a throughput of 90%. The transmission is mostly limited by the difference of the reflection coefficients of the two mirrors of the cavity. This result paves a way to the fabrication of filters with ultra-narrow bandwidth, high transmission and broadband rejection width.

5. ACKNOWLEDGMENTS

This work has been partially supported by HEL JTO contract W911NF-10-1-0441 and NASA contract NNX09CB49C. Julien Lumeau's research stay the Fresnel Institute has been supported by IMI through the NSF Grant# DMR-0409588. Julien Lumeau thanks Dr Fabien Lemarchand for his help in characterizing the fabricated filters.

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